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Procedia - Social and Behavioral Sciences 43 (2012) 475 – 493

Procedia
Social and Behavioral Sciences

8th International Conference on Traffic and Transportation Studies
Changsha, China, August 1–3, 2012

Modeling of Traffic Flow on Indian Expressways using Simulation Technique

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Abstract

Expressways in India are vastly different from other roads of the country as bicycles, two-wheelers, three-wheelers and bullock carts are not allowed to ply on these facilities and the traffic essentially consists of cars and trucks. Nevertheless, there is not much research literature specific to these categories of roads. Hence, this work aims to model traffic flow on Indian Expressways by evaluating Passenger Car Unit (PCU) or Passenger Car Equivalents (PCE) of different vehicle categories at different volume levels in a level terrain using the micro-simulation model, VISSIM. This work also aims to evaluate capacity of expressways and to study the effect of vehicle composition on PCU values. It has been found that PCU decreases with increase in volume-capacity ratio irrespective of vehicle category. The study also revealed that at a given volume level, the PCU of a given vehicle category decreases when its own proportion in the stream increases.

Keywords: heterogeneous traffic flow, expressways, simulation, pcu, roadway capacity

1. Introduction

In Indian terminology, an expressway is defined as an arterial highway for motorized traffic, with divided carriageways for high speed travel, with full control of access and usually provided with grade separators/interchanges at location of intersections. These are six or eight-lane highways with only fast moving vehicles plying on them. Indian Government initiated the construction of expressways only in the

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doi:10.1016/j.sbspro.2012.04.121

last decade and currently there are about 600 km of these roads in the country of which Ahmedabad-Vadodara and Mumbai-Pune Expressways are salient examples. Expressways deserve to be treated separately from other categories of roads as these facilities carry only relatively large vehicles such as cars, buses and trucks. Expressways are not generally accessible by vehicle categories such as bullock carts, cycles, two-wheelers and three wheelers that typify traffic in India. Hence expressways can be considered to be in midway between freeways in the developed countries such as United States where there is a huge proportion of cars and other categories of roads in India which carry 10 or more vehicle categories inclusive of bullock carts, cycles, two-wheelers, three wheelers, cars, trucks and buses.

Traffic flow in Indian expressways is quite interesting to be studied due to two reasons. First, the traffic is multi-class with vehicles such as cars and pickups with their high maneuverability and heavy vehicles such as trucks and buses. The speeds of these vehicles may vary from 20 to over 100 km/h. Second, in spite of absence of vehicles such as two-wheelers and three wheelers that can clog the traffic during congestion, driving in expressways is said to be quasi-lane disciplined, with some vehicles following a lane-based driving and many others not. Such a lack of lane discipline can be attributed to combination of factors viz. enforcement and education. Indian drivers are not educated about the importance of sticking to their lanes other than for overtaking and improving driving speeds. There are neither video cameras mounted at select locations of the roads nor a central monitoring system that reports violations. Consequently vehicles tend to take any lateral position along the width of roadway, based on space availability. When such different types of vehicles with varying static and dynamic characteristics are allowed to mix and move on the same roadway facility, a variable set of longitudinal and transverse distribution of vehicles may be noticed from time to time. Hence expressways remain as a partially heterogeneous traffic characterized by poor lane discipline. Given this significant difference in the nature of traffic flow in expressways in relation with other kind of roads in India as explained above, there are not much research work on either design or operation of these facilities. This may also be attributed to the recent origin of Expressways in India and also lack of experience in analyzing such types of partially heterogeneous facilities.

Under heterogeneous or partially heterogeneous conditions, expressing traffic volume in terms of vehicles per hour per lane is irrelevant as there is either no or partial lane discipline. One way to represent the heterogeneous traffic flow is to express each vehicle category in terms of the interference it causes to the flow in terms of a standard vehicle category such as car. Such a measure is called the Passenger Car Unit (PCU) as known in India or Passenger Car Equivalent (PCE) worldwide. In general, heterogeneous flows are expressed as PCU per hour taking the whole width of the carriageway into account. But there are many complexities in expressing a vehicle as its equivalent PCU. PCU values of any vehicle are sensitive to factors such vehicle composition in the traffic mix and speed of the stream. Hence adopting a single PCU for a given vehicle is not accurate but rather a dynamic or stochastic PCU that accounts for all the factors should be adopted. But such a universal PCU estimation for heterogeneous traffic flow is not available considering the so many possible combinations of vehicle composition and speeds that could be observed in the field.

For correct estimation of PCU values, it is necessary to study accurately the influence of roadway and traffic characteristics and the other relevant factors on vehicular movement. Study of these complex characteristics in the field is difficult and time consuming. Also, it may be difficult to carry out such experiments in the field covering a wide range of roadway and traffic conditions. Hence, it is necessary to model road–traffic flow for in depth understanding of the related aspects. The study of these complex characteristics, which may not be sufficiently simplified by analytical solution, can be done using alternative tools like computer simulation. Simulation is already proven to be a popular traffic-flow modeling tool for developing various applications related to the traffic flow on roads. VISSIM is one of the most widely accepted simulation package for simulation of both homogenous and heterogeneous traffic flows.

The objective of this study is to estimate and study the possible variation of Passenger Car Unit (PCU) values of different categories of vehicles at various traffic volume levels under heterogeneous traffic conditions prevailing on basic expressway sections of India in level terrain. VISSIM is used to model the heterogeneous traffic-flow. Field data collected on traffic flow characteristics such as free speed, acceleration, lateral clearance between vehicles, etc. are used for calibration and validation of the simulation modeling VISSIM. The validated simulation model is then used to derive Passenger Car Unit (PCU) values for different types of vehicles.

2. Literature review

Simulation has been recognized as one of the best tools for modeling of traffic flow under homogeneous as well as heterogeneous conditions. Fellendorf and Vortisch (2001) presented the possibilities of validating the microscopic traffic flow simulation model VISSIM, both on a microscopic and a macroscopic level in homogeneous flows. Matsuhashiet. al. (2005) assessed the traffic situation in Hochiminh city in Vietnam, using image processing technique and traffic simulation model (VISSIM). It was found that the high number of motorcycles in the network interfere with other vehicles which reduces average speed of traffic stream drastically. Further, the simulation model was applied for deriving the benefits of increasing the share of public transport. Zhang et al. (2008) conducted a study using VISSIM to evaluate a proposed feedback- based tolling algorithm to dynamically optimize High Occupancy Toll (HOT) lane operations and performance. Hossain (2004) calibrated the heterogeneous traffic model in VISSIM to match saturation flows measured by video at an intersection in the city of Dhaka, Bangladesh. Velmurgan et al., (2010) studied free speed profiles and plotted speed–flow equations for different vehicle types for varying types of multi-lane highways based on traditional and microscopic simulation model VISSIM and subsequently estimated roadway capacity for four-lane, six-lane and eight-lane roads under heterogeneous traffic conditions with reasonable degree of authenticity.

Many researchers tried to build their own simulation software for studying heterogeneous traffic flow. Arasan and Koshy (2005) developed a heterogeneous-traffic-flow simulation model to study the various characteristics of the traffic flow at micro level under mixed traffic condition on urban roads. The vehicles are represented, with dimensions, as rectangular blocks occupying a specified area of road space. The positions of vehicles are represented using coordinates with reference to an origin. For the purpose of simulation, the length of road stretch as well as the road width can be varied as per user specification. The model was implemented in C++ programming language with modular software design. The model is also capable of showing the animation of simulated traffic movements over the road stretch. Dey et al. (2008) developed a simulation program coded in Visual Basic language. The authors performed number of simulation runs to determine the capacity of a two-lane road and to study the effect of traffic mix, slow moving vehicles and directional distribution of traffic on capacity and speed.

In the developed world such as Europe, United States, Canada and Australiathe traffic flow is homogeneous with cars and trucks being the two main categories of vehicles. Researchers in traffic flow in these countries have used Passenger Car Equivalents (PCE) for converting trucks into equivalent car units for capacity and level of service estimation. A review of existing literature reveals that many different methods have been used for estimation of PCE values. PCE can be estimated based on (i) delay (Craus et al (1980), Keller and Saklas(1984)), (ii) speed (Linzer et al(1979), Van Aerde and Yagar(1984)), (iii) density (Huber (1982), Webster and Elefteriadou(1999)), (iv) headway (Werner and Morall(1976), Krammes and Crowley(1986)) and (v) queue discharge(Al-Kaisy et al(2002), Al-Kaisy et al(2005)).As all these studies have confined themselves to estimation of PCE for heavy vehicles only (Trucks or Buses) under homogeneous traffic, the results of these studies are not applicable for Indian conditions where heterogeneous traffic with ten different categories of vehicles.

There have been many studies in India on where PCE is called PCU or Passenger Car Unit. Chandra *et al*. (1995) and Chandra (2004) proposed a methodology to derive dynamic PCU values based on the relative space requirement of a vehicle type compared to that of a passenger car as the basis of measure. They developed a mathematical model for PCU estimation as the ratio of the speed and projected area ratio of car and subject vehicle. Chandra and Kumar (2003) studied the effect of road width on PCU of vehicles on two-lane highways and found that the PCU value increased with increase in width of roadway. Basu *et al*. (2006) developed a Neural Network (NN) model to study the non-linear effect of traffic volume and its composition level on the stream speed. The effect of traffic volume and composition on PCE for different types of vehicles under mixed traffic condition was investigated for an urban mid-block section. It was found that the PCE of a vehicle type varies in a non-linear manner with traffic volume and composition. There have been many studies aimed at assessing the roadway capacity for varying carriageway widths including single lane, intermediate lane, two-lane bi-directional, four-lane and six-lane highways (Tiwari, et. al., (2000), Velmurugan et. al. (2002), Chandra and Kumar (2003), Chandra (2004), Velmurugan et. al. (2009) and Arkatkar and Arasan (2010)) during the last two decades.

Due to the recent origin of Expressways in India, there are not many studies on Indian Expressways even after fifteen years of their advent. The governing document of Indian Ministry of Road Transport and Highways on Expressways(MORTH(2010)) that is based on HCM 2000 gives PCU values of trucks according to the location of the road i.e.in a urban or rural setting and also according to the terrain viz. level, rolling or mountainous. It also suggests PCU values as per the configuration of the road and percentage of trucks on it. There is no other document or research work in India to the best of authors' knowledge. The above review of literature clearly shows that there are many research works available in PCU estimation of heterogeneous flows using simulation for four-lane or six-lane highways. Nevertheless it is also clear that there is no study on Expressways of India in spite of the fact that Expressways are vastly different from other facilities in terms of design and operation as explained above.

3. The Simulation model

Simulation technique is one of the well-known techniques to study traffic flow and its characteristics. Simulation gives us the advantage of being able to study how the created model behaves dynamically over time or after a certain span of time. Traffic characteristics on roads as a system vary with time and with a considerable amount of randomness and simultaneous interactions. The most difficult and critical process in simulating any traffic flow scenario or for that matter any physical phenomena is to calibrate the simulated model to capture or replicate the ground reality with the desired accuracy. Given this, the results obtained through a validated simulation model would be more accurate than those obtained through analytical results. Also, simulation gives us the freedom to ascertain the sensitivity of any traffic flow parameter such a composition with any other parameter such as PCU.

The simulation model followed in the present study is shown in the form of a flow chart in Fig. 1. Data in the form of videos collected from the study site was analyzed and this information is used for building the simulation model in the software VISSIM 5.30. Then the model was calibrated and validated for rendering it suitable for replicating the conditions at site. Using this validated simulation model, roadway capacity estimation and PCU estimation were done.

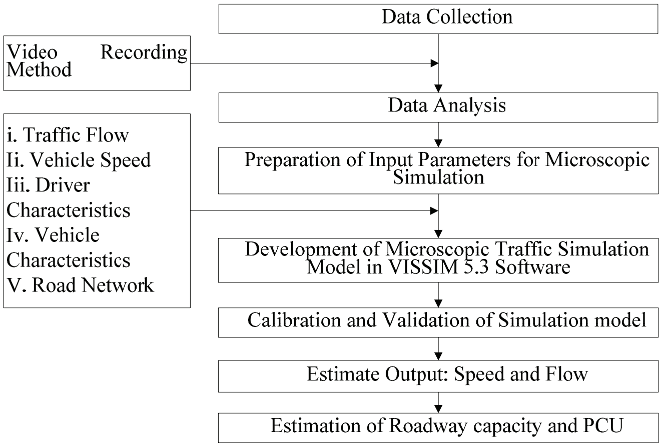

Fig. 1. Simulation model

4. Model calibration and validation

Model calibration is an iterative process of comparing the model to reality, making adjustments (or even major changes) to the model, comparing the revised model to real conditions, making additional adjustments, comparing again, and so on. The comparison of the model to reality is carried out by tests that require data on the system's behavior plus the corresponding data produced by the model. The input data required for the above mentioned heterogeneous traffic-flow model are related to four aspects viz. road geometrics, traffic characteristics, driver reaction time and vehicle performance. The power of simulation as a tool for the study of traffic flow lies in ability of the model to include the effect of the random nature of traffic. Hence, the random variables associated with traffic flow such as headway distribution are expressed as frequency distributions and input into the simulation model. These data, pertaining to one direction of traffic flow, was collected at a selected stretch of an expressway for model calibration and validation purposes.

5. Study stretch

The road stretch selected for the study is Mumbai-Pune Expressway in Western India. The location for data collection is 9.1 km away from Pune city on the expressway. The study stretch was selected after conducting a reconnaissance survey such that it satisfies the following conditions: (1) The stretch should be fairly straight, (2) Width of roadway should be uniform and (3) There should not be any direct access from the adjoining areas. The study stretch is a six lane divided road with a central median of 5.0 m width. The width of main carriagewayin one direction of traffic flow is 10.5mand the paved shoulder width is 1.3 m.

6. Data collection

The field data input required for the model were collected at the above location with the help of a digital video camera for capturing the traffic flow movement for a total duration of one hour. The video was then analyzed at a speed one-eighth of the actual speed to enable recording and measurement of data. For the study hour, the traffic volume observed was 1087 vehicles per hour whose composition is given in Column (2) of Table 1. The speeds of the different categories of vehicles were measured by noting the time taken by the vehicles to traverse a trap length of 30 m. The free speeds of the different categories of vehicles were also measured for the traffic under free-flow conditions. The observed maximum, minimum and mean speeds of various classes of vehicles and the corresponding standard deviations are shown in columns (3), (4), (5) and (6) respectively of Table 1.

The overall dimensions of all categories of vehicles are shown in columns (7) and (8) of Table 1. Any vehicle moving in a traffic stream has to maintain sufficient lateral clearance on the left and right sides with respect to other vehicles/ curb/ median to avoid side friction. These lateral clearances depend upon the speed of the vehicle being considered, speed of the adjacent vehicle in the transverse direction, and their respective vehicle categories. The minimum and maximum values of lateral-clearance share are given in columns (9) and (10) of Table 1 respectively. The minimum and the maximum clearance-share values correspond to zero speed and free speed conditions of respective vehicles respectively. The acceleration values of the different categories of vehicles over different speed ranges used for simulation are shown in Table 2.

Table 1. Input data for heterogeneous traffic flow simulation

Vehicle category (1)	Composition (%) (2)	Observed speeds (km/h)				Vehicle dimension (m)		Lateral-clearance share (m)	
		Max. Speed (3)	Min. Speed (4)	Mean Speed (5)	Std. Deviation (6)	Length (7)	Width (8)	Min. (9)	Max. (10)
Truck	4.60	69	48	60	9.36	8.5	2.5	0.4	1.0
Bus	3.80	93	64	79	17.25	11.4	2.5	0.4	1.0
Car	86.30	102	78	90	11.70	4.9	1.9	0.5	1.0
MAV	1.90	62	40	53	12.53	8.0	3.0	0.4	1.0
LCV	3.40	80	63	73	8.67	6.0	1.9	0.4	1.0

Note: Truck- 2-axle trucks, MAV- Multi-axle (more than two axles) trucks, LCVs – Light Commercial Vehicles.

Table 2. Acceleration values for different vehicle categories

Vehicle Type	0-30km/hr(m/s^2)	30-60km/hr(m/s^2)	Above 60 km/hr(m/s^2)
Car	2.20	1.70	1.00
Bus	1.00	0.70	0.50
Truck	1.10	0.58	0.34
LCV	1.30	0.90	0.60
MAV	0.80	0.60	0.30

7. Simulation model development

A model which accurately represents the design and operational attributes of the study stretch in the simulation software is known as the 'base model'. The design attributes can be road configuration (carriageways, medians& shoulders), horizontal curvature and vertical gradient. Operational attributes can be the vehicle or driver characteristics and the traffic flow data. When this base model is calibrated and validated to replicate the actual or ground conditions, the model can be used to study different characteristics that were not defined by the user as an input. For example, the width of the road can be defined and in turn the capacity of this road could be measured. The validated base model can also be used to develop a simulated scenario which is desired to be known. The base model development involves the following steps: (a) Development of Base Link/Network. (b) Defining Model Parameters. (c) Calibrating the Network. (d) Validating the Model.

7.1 Development of base Link/network.

Development of a link/network that accurately depicts the physical attributes of a test site is an important stage in the modeling process. The basic key network building components in VISSIM are links and connectors. In the present simulation model, a unidirectional three lane test section link spanning 1000 m was created representing the study stretch located on the Mumbai-Pune Expressway as explained above. Additionally, extra links of length 200 m each were provided at the beginning and end of the main stretch for buffering process. The test section and the buffer links were joined using the connectors. The buffer links provided the spatial warm up sections for vehicles entering and exiting the test section thereby ensuring accurate results.

7.2 Defining model parameters

(1) Vehicle model.

Vehicle model deals with defining the dimensions of each vehicle type that are plying on the test stretch and are hence considered for the simulation. It is also used to define the acceleration values of vehicles. The dimensions namely the width and the length are considered for the present simulation model as per the description given in Table 1. The acceleration values are given as per Table 2.

(2) Desired speed distribution.

The desired speed distribution for each vehicle category was given as input for the simulation model in VISSIM. The maximum& minimum values of the speeds and distribution between these values were defined in the model. The desired speed profile for the vehicle type car is given as an example is shown in Fig. 2. The desired distribution curve for any vehicle category is generally an ‘S’ shaped curve as shown in the figure. Adequate care was taken to ensure that the speed distribution defined in VISSIM represented the values observed in the field.

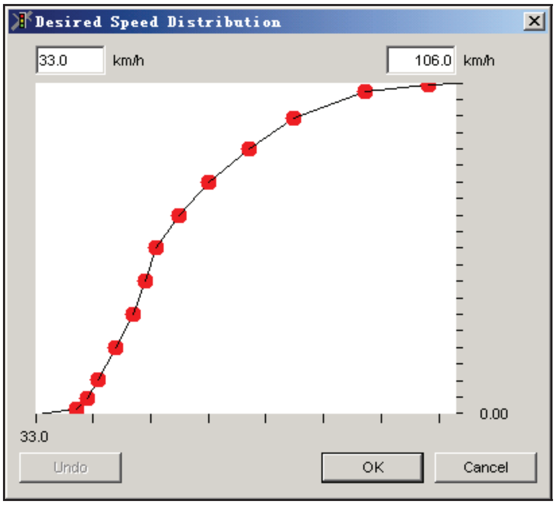

Fig. 2. Desired speed distribution of car considered in VISSIM

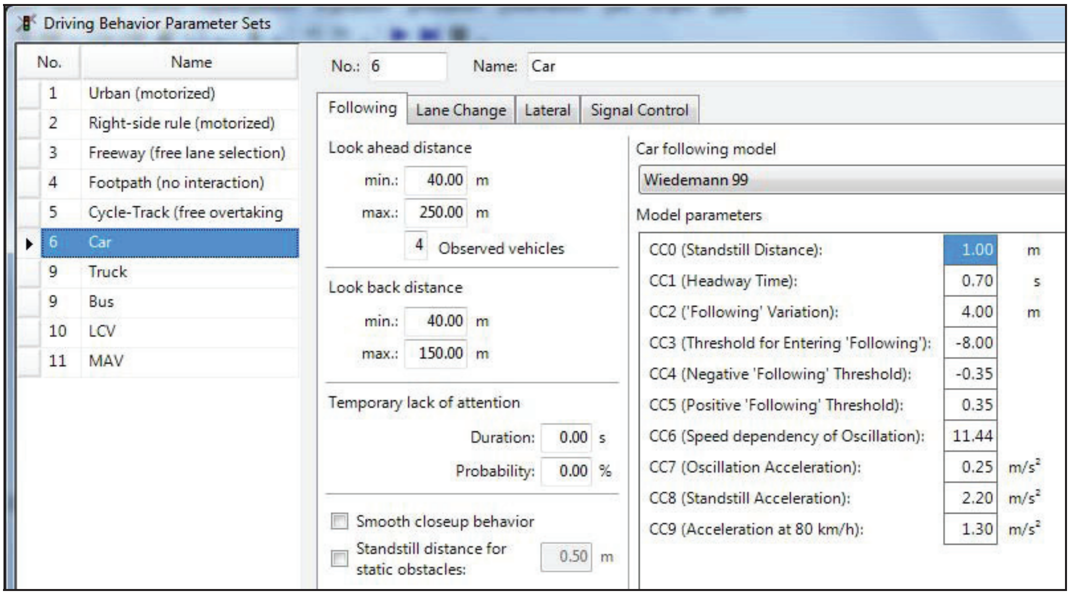

Fig. 3a. Car following parameters considered in simulation

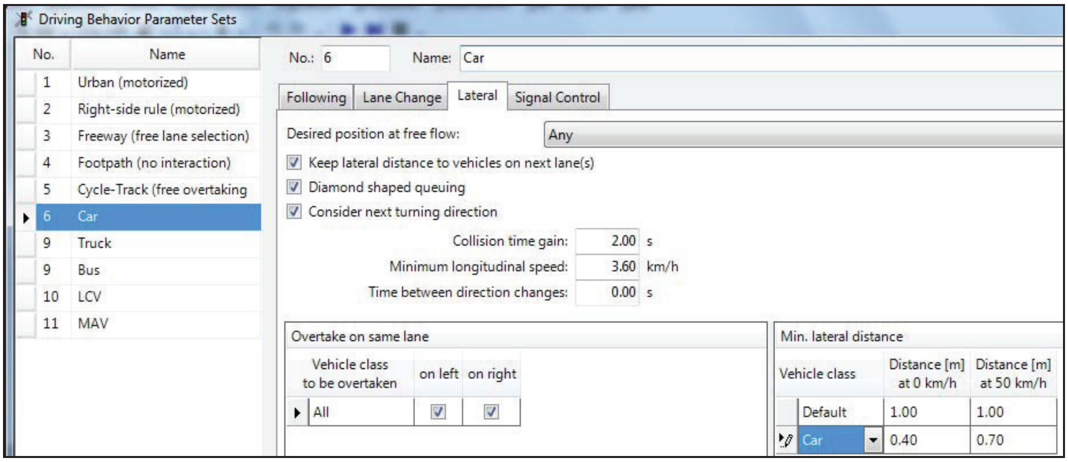

Fig. 3b. Lateral distance parameters considered in simulation

(3) Vehicle composition and Vehicle Flow.

Vehicle composition and vehicle flow based on field observations is given as an input to simulation model for the given time interval.

(4) Driving behavior characteristics.

The driving behavior characteristics mainly include these two features viz. car following behaviour and lateral distance. These inputs were given in the simulation model as shown in Fig. 3a and 3b respectively. The psycho-physical driver behaviour based Wiedermann 99 Car-following model has been used for simulating the vehicle following behaviour. The parameters of this car-following model including safety distance during standstill, minimum time headway are shown in Figure 3a.For defining the lateral distance between the vehicles the location of the vehicle on a lane, minimum lateral distance at different speeds etc. were given as input. Every vehicle type is assigned with its own driving behaviour as shown in the Fig. 3b.

7.3. Calibration of the Simulation Model

Calibration is a process of adjusting the model to replicate observed data and observed site conditions to a sufficient level to satisfy the model objectives. This process involves adjusting the following characteristics: desired speed distribution, acceleration/deceleration of vehicle, mechanical characteristics of the vehicle, minimum safety distance, minimum lateral distance and driving behaviour characteristics.

By giving these parameters as an input to simulation model, simulation runs have to be carried out in order to estimate the output. In the present simulation model, the outputs were the traffic volumes and average speeds of the vehicles for 10 different random seed values. All the simulations were run for a total time of 3900 seconds including a temporal warm-up period of 300 seconds to ensure accurate simulation results. As explained above, a different driving behaviour was considered for each vehicle type to account for heterogeneity in the traffic. There was no strict lane discipline among the vehicles was as observed from the video. Hence an entire road width based simulation where there was a one lane model having an effective with of three lanes was considered in the simulation. Thus each vehicle was free to choose any lateral position and overtake from any side during the simulation on this three lane width without any lane discipline similar to site conditions.

The minimum look ahead distance which defines the distance a vehicle can see forward in order to react to vehicles in front or to the side of it was set to a value of 40 m was found to be appropriate for the present situation. Similar calibration was done for minimum look back distance. Time headway plays a major role for capacity estimation in VISSIM and hence these values were chosen carefully for each vehicle type according to the observed traffic flow as shown in the figure 3a. The other values were chosen as per the defaults considered in VISSIM which produced the observed conditions with required accuracy. The estimated values and the observed values were compared and the error was computed. If the error was within the limits, the calibration process was stopped or otherwise the parameters were modified and simulation runs were carried out. This process was repeated and the simulation runs were made till the error was within the satisfactory limits. The calibration process in the form of a flow chart is shown in Fig. 4.

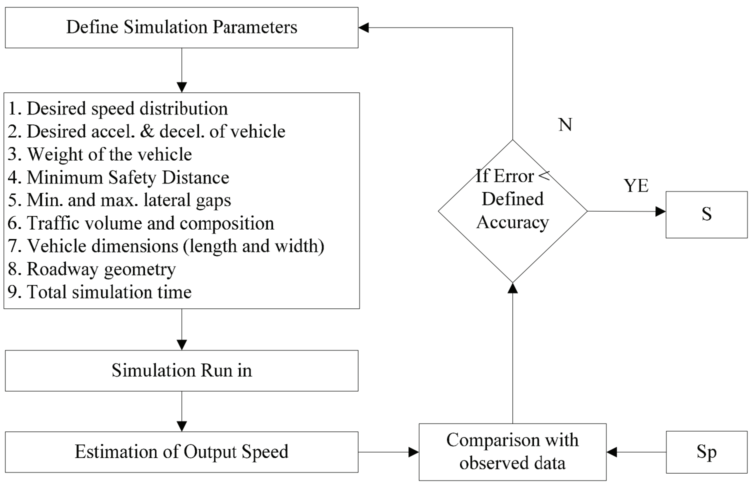

Fig. 4. Calibration of the simulation model

7.4. Validation of the simulation model

Validation is the process of checking the results obtained from the calibrated model in terms of simulated values against field measurements for parameters such as traffic volumes and average speeds. The observed traffic volume and composition was given as input to the simulation process. The simulation runs were made with 10 random number seeds for a total run time of 3900 seconds including temporal warm-up period of 300 seconds to ensure accurate simulation results. A sample simulation run is shown in Figure 5. The average speeds of vehicles from a single run was noted and then the average speed for each vehicle category from all the ten runs were taken as the final output from the model. The inter-arrival time gaps of the heterogeneous traffic flow (similar to headway of homogeneous traffic) of vehicles was assumed to follow negative exponential distribution(Arasan and Koshy, 2003) and the free speeds of different categories of vehicles, based on the results of an earlier study (Velmurganet al. 2010)), was assumed to follow normal distribution. These distributions formed the basis for input of the two parameters for the purpose of simulation. To check for the validity of the model, the vehicle speeds simulated by the model were compared with the field observed speed values for each vehicle category. The comparison of the observed and simulated speeds, for an observed traffic volume of 1087 vehicles per hour, is shown in Fig. 6.

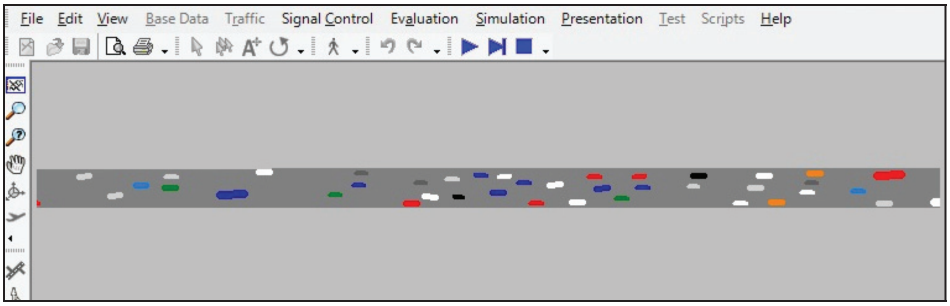

Fig. 5. A snapshot of simulation run in VISSIM

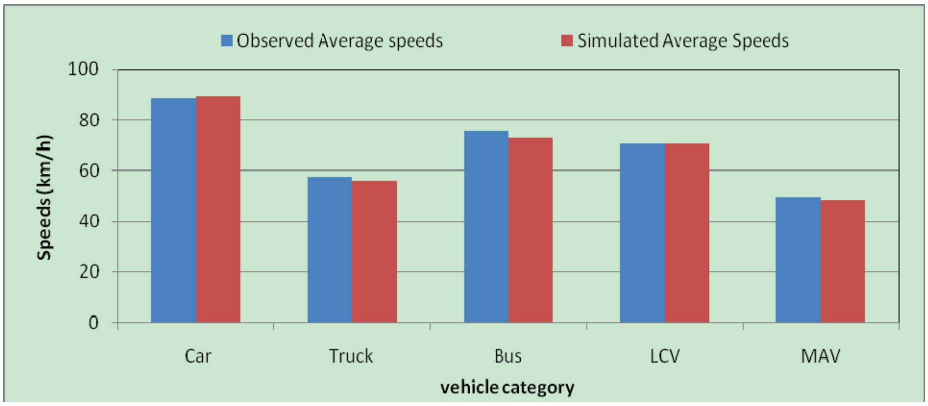

Fig. 6. Comparison of observed and simulated speed

It can be seen that the simulated speed values are quite closer to the speeds observed from the field for all the vehicle categories. A paired t-test yielded the calculated value of t-statistic (t_0) as 1.59. The critical value of t statistic for a level of significance of 0.05 for 4 degrees of freedom obtained from standard t-distribution table is 2.776. This implies that there is no significant difference between the observed and simulated speeds.

(1) Model application.

The VISSIM model can be applied to study various traffic scenarios for varying roadway and traffic conditions. In this study, the application of the model is to study the relationship between traffic volume and speed on Indian Expressways with five categories of vehicles as shown in Fig. 6. It has also been used to quantify the relative impact of each category of vehicle on traffic flow by estimating their PCU values at different volume levels under heterogeneous traffic conditions prevailing on Indian expressways. Further, the model has been used to study the effect of vehicle composition on the PCU value of different categories of vehicles at a given volume level.

(2) Speed-flow relationships and capacity.

One of the basic studies in traffic flow research is to examine the relationship between speed and volume of traffic. The capacity of the facility under different roadway and traffic conditions can be estimated using these relationships. In this study, speed-flow relationship was developed using the validated simulation model for a heterogeneous flow with vehicle composition and roadway conditions same as that observed in the field. The average speed of the stream was plotted for different simulated volumes, starting from 200 vph to the capacity of the road. Additionally, speed-volume relationships considering simulated traffic flow with 100% composition for different categories of vehicles were plotted for volume levels starting from near-zero until capacity of the facility.

The following procedure was adopted for finding the capacity of the facility when developing the above speed-flow relationships. During successive simulation runs with increments in traffic volume from near-zero volume level, there will be a commensurate increase in the exit volume at the end of simulation stretch. After a specific number of runs, the increments in the input traffic volumes will not result in the same increase in the exit volume. Such a decrease in exit volume (in spite of increase in the input) in successive runs indicates that the facility has reached its capacity. The speed-volume relationships for a six lane expressway are shown in the Figs. 7 through 10. It is clear from the figures that the curves follow the established trend and the capacity in terms of vehicles per hour decreases as we proceed from car, light commercial vehicle and trucks in that order, which is quite intuitive. The values of capacity obtained from the simulation for the observed flow and simulated one vehicle type flows are given in Table 3.

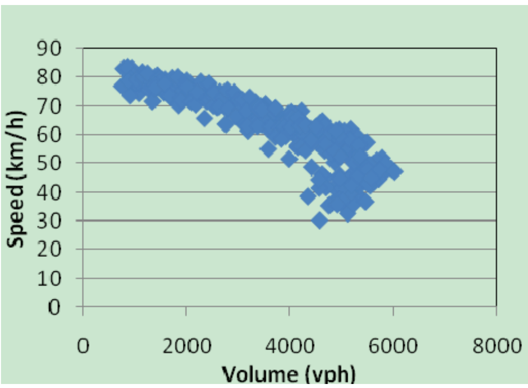

Fig. 7 Observed traffic Flow

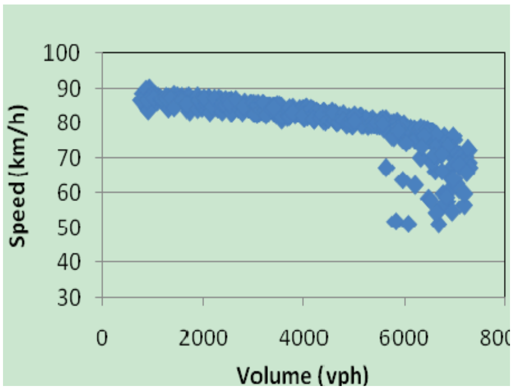

Fig. 8 Cars only- traffic flow

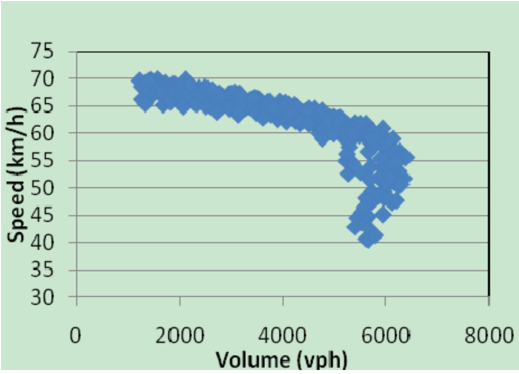

Fig. 9. LCV only- traffic flow

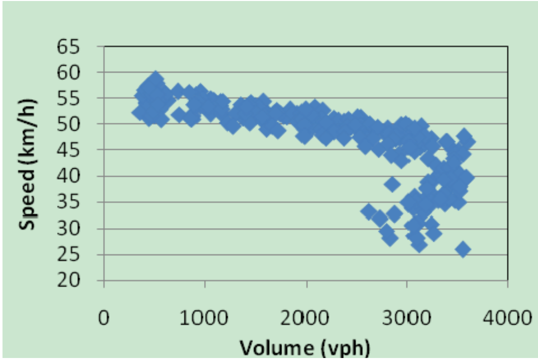

Fig. 10. Trucks only- traffic flow

Table 3. Estimated roadway capacity of six lane expressways

Flow Type	Traffic Composition	Estimated Capacity (veh/hr/dir)
Observed	Heterogeneous (Table 1)	5964
Simulated	100% car	7297
Simulated	100% trucks	3600
Simulated	100% LCV	6392

7.5. Estimation of PCU values

As explained in the introduction, capacity of a highway facility with heterogeneous traffic flow with vehicles of widely varying static and dynamic characteristics is best expressed in terms of PCU. Different vehicle categories such as light commercial vehicles, trucks and multi-axle vehicles are expressed into equivalent PCU. This necessitates an accurate estimation of PCU which varies dynamically with various traffic flow parameters such as stream speed, vehicle composition and volume-capacity ratio. Chandra (2004) developed the concept of dynamic PCU considering the various traffic interactions and flow characteristics. The PCU for a vehicle was calculated using Eq. (1).

$$PCU_i = \frac{V_c/V_i}{A_c/A_i} \tag{1}$$

where PCU_i is the PCU of the subject vehicle *i*; V_c=Average speed of cars in the traffic stream, V_i= Average speed of subject vehicle *i*; A_c=Projected rectangular area of a car and A_i= Projected rectangular area of the vehicle type *i*.

To emphasize their dynamic nature, PCU values for different categories of vehicles under heterogeneous traffic conditions at eight different volume-capacity (V/C) ratios viz. 0.125, 0.250, 0.375, 0.500, 0.625, 0.750, 0.875 and 1.000 were estimated using simulation. The capacity values for the calculation of these V/C ratios were obtained from the speed flow graphs. For the purpose of simulation, eight traffic volume levels corresponding to these V/C ratios with same composition as observed in the field (as in Table 1) were considered. Outputs obtained from simulation runs served as inputs for Equation 1for calculating the PCU values of different types of vehicles at different volume levels. The computed values are shown in Table 4.

Table 4. PCU Estimates of different vehicles at different V/C ratios

V/C ratio	Truck	Bus	LCV	MAV
0.125	4.31	3.78	1.88	5.39
0.250	4.11	3.58	2.04	4.81
0.375	4.39	3.61	1.87	5.07
0.500	4.12	3.62	1.87	5.16
0.625	4.01	3.57	1.87	4.40
0.750	3.77	3.63	1.84	4.08
0.875	3.80	3.48	1.85	4.06
1.000	3.59	3.46	1.81	3.75

It can be seen from the table that the PCU values are the highest for multi-axle vehicles, followed by truck, bus and light commercial vehicles in that order, this being irrespective of the V/C ratio. These results are quite intuitive: the heavier the vehicle, the lesser its manoeuvrability, the greater its hindrance to other vehicles and greater is its PCU. It can also be observed that the PCU value for a given vehicle category decreases as V/C ratio increases. This phenomenon could be explained by the fact that the speed difference between the subject vehicle category and the reference vehicle (car) decreases as V/C ratio increases. The respective speed difference trend between different vehicle categories and cars is given in Fig. 11.

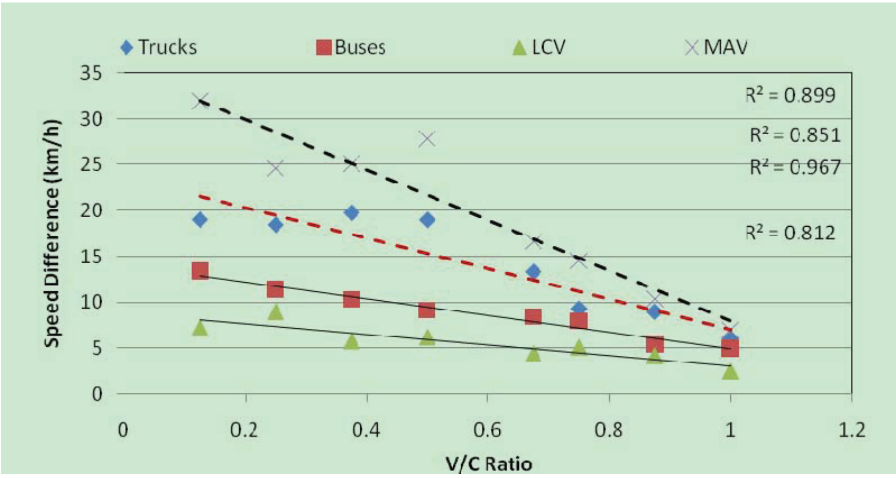

Fig. 11. Speed difference between different vehicle categories and cars

(1)Effect of vehicle composition on PCU values.

The effect of composition on the PCU values of different categories of vehicle was studied in the following manner. Firstly, a cars only traffic stream was simulated, speed flow relationship developed as explained above and the capacity of the facility was found. Similarly, different proportions (10, 20, 30, 40 and 50%) of trucks were added in these cars only traffic stream and simulations were run, and the capacity was estimated. The results of this study are given in Fig. 12 according to which the capacity of the facility decreases as the proportion of trucks in the stream increases which is again intuitive.

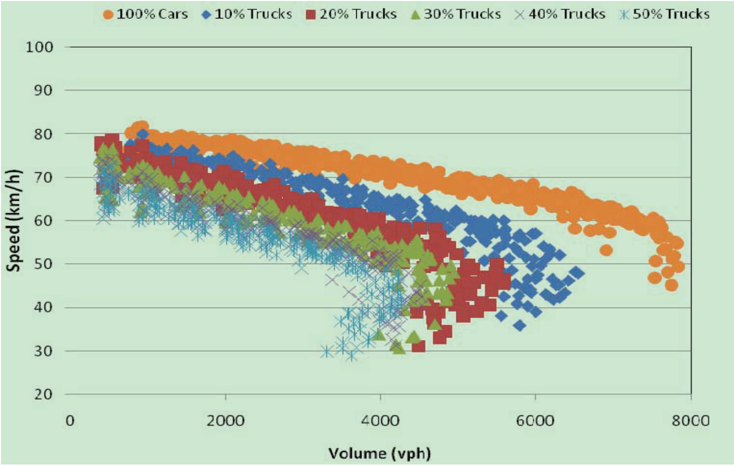

Fig. 12. Speed-flow relationships of cars only and cars& trucks traffic stream

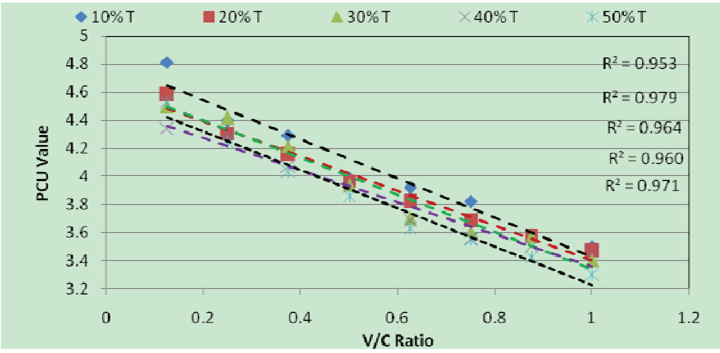

Fig. 13. Variation of PCU value of trucks with V/C ratio and percentage trucks in the stream

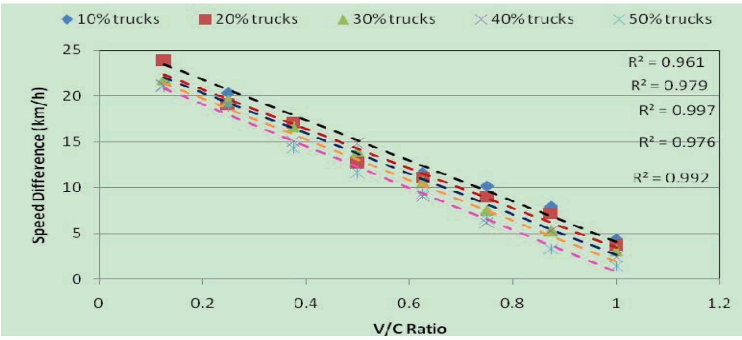

Fig. 14. Speed difference between trucks and cars at different truck proportions

The capacity estimated from the above speed-flow relationships for different compositions were used to find the V/C ratios and the PCU values of trucks as an example at each V/C ratio were found again using Equation (1). These PCU values have been plotted in the form of a graph in Fig. 13 from which the following observations could be made. The PCU value of trucks decreases as the V/C ratio increases which is due to the observed speed difference between trucks and cars as shown in Fig. 14. One more interesting observation is that the PCU value of truck decreases as proportion of trucks in the traffic stream increases which is due to ‘platooning effect’ of trucks(Webster and Elefteriadou (1999)). Similar results were obtained for other categories of vehicles viz. bus, multi-axle vehicles and light commercial vehicles considered in this study.

(2) Check for accuracy of PCU values

For the purpose of checking the accuracy of the PCU estimates for different vehicle categories the following procedure was adopted. Firstly, the heterogeneous traffic flow with same vehicle composition as observed in the field for eight different V/C ratios was simulated for an hour and the number of vehicles passing the simulation stretch, in each category during each run was noted. Then the vehicles of the different categories were converted into equivalent PCUs by multiplying the number of vehicles in each category, by the corresponding PCU values (Table 8). The products, thus obtained, were summed up to get the total traffic flow in PCU/hour. Similarly a traffic stream consisting only cars was also simulated for an hour for the same set of V/C ratio values. Thus the traffic volume in terms of number of cars was obtained for the set of selected V/C ratios. Comparison of the traffic flows measured in terms of PCU and in terms of number of passenger cars, for the set of the selected V/C ratios is shown in both Table 5 and Figure 15. It can be seen that the traffic flow in PCU/hour and vehicles/hour in cars-only flow match fairly well at each V/ C ratio indicating the accuracy of the estimated PCU values. Table 5 also gives the difference between the two values in the form of an error term.

A paired t-test based on the two values was also done in which the calculated value of t-statistic (t_0) was 0.407. The critical value of t-statistic for a level of significance of 0.05 for 7 degrees of freedom, obtained from standard t-distribution table is 2.37. This implies that the difference between the volumes measures in terms of PCU/hour and cars/hour implying that the estimated PCU values for different vehicles are fairly accurate.

Table 5. Comparison and checking of estimated PCU values

V/C ratio	0.125	0.250	0.375	0.500	0.625	0.750	0.875	1.000
Cars/hour	971	1970	2942	4013	4880	5904	6842	7297
Total flow(PCU/hr)	902	2070	2983	4313	4973	5870	6823	7595
Error(%)	-7.65	4.83	1.37	6.96	1.87	-0.58	-0.28	-3.92

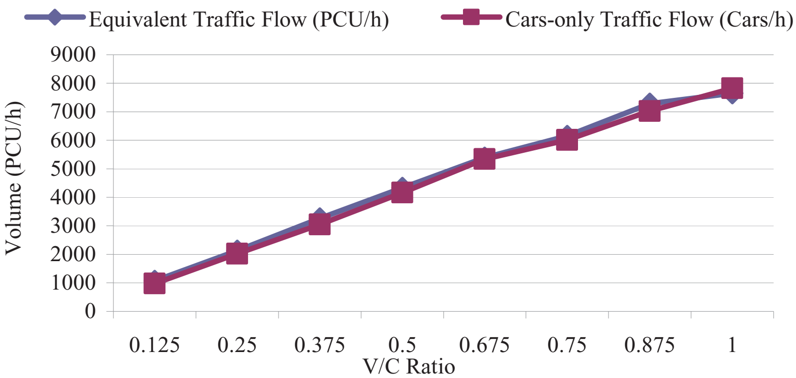

Fig. 15. Comparison of heterogeneous traffic and cars-only traffic flows

8. Limitations of the study

The following are the limitations of the current study: (1) The effect of heterogeneity in terms of vehicle composition in the traffic stream on PCU has not been accounted for in the study. Though the PCU values at different V/C ratios have been calculated, it has been done under the same composition as observed in the field. (2) The driver behaviour, considered in this study can be refined further to consider many more physiological and psychological factors.

9. Future research scope

This study can be further extended to study the following aspects: (1) Developing the concept of stochastic capacity estimates under heterogeneous traffic conditions prevailing on expressways in India. Such estimates would account for vehicle composition in the traffic stream. (2) Studying lane utilization and lane discipline in Indian Expressways to determine the degree of heterogeneity in these facilities with clear demarcation between vehicles following a lane discipline and those who do not.

10. Comparisons with works in other countries

10.1 Speed flow relationships

The traffic flow in the developed countries like the US is homogeneous with a large proportion of cars and with a strict lane discipline. Expressways in India are far less heterogeneous than other categories of the roads in the country in that they are devoid of small vehicles such as bicycles, two-wheelers, three wheelers and bullock cart that may really clog the traffic. Nevertheless they still remain partially homogeneous as there is no strict lane discipline on this type of roads. Hence vehicles in Indian expressway have the freedom to occupy any lateral position on the road leading to more frequent and unwarranted lane change maneuvers. This results in a decrease of speed of the facility with increase in volume at a faster rate than that observed for homogeneous traffic in developed countries. It is also interesting to note that the rate of decrease of speed for expressways with cars only traffic stream with no lane discipline is slower than that observed for expressways with all the categories of vehicles. These inferences can be drawn from Figs .7, 8 and 16.

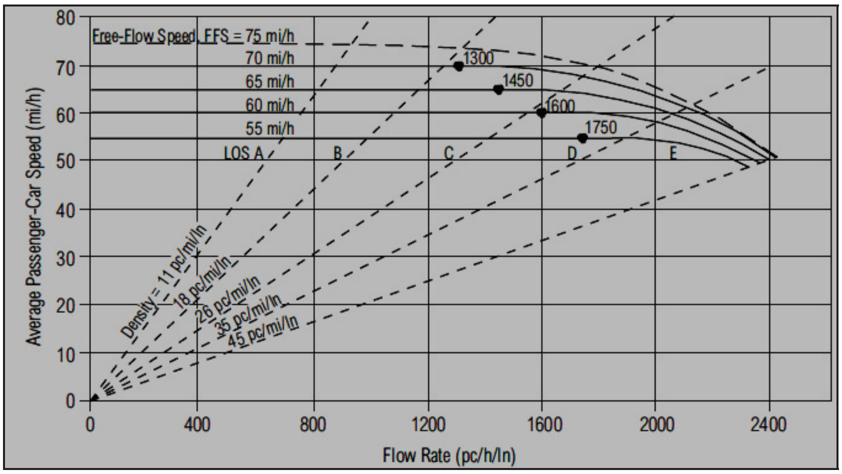

Fig. 16.Speed flow curve for homogeneous traffic (source: TRB (2000))

10.2. PCU values

The magnitude of PCU values of heavy vehicles such as buses, trucks, and light commercial vehicles in heterogeneous traffic in Indian expressways is found to be higher than the static PCU value of trucks (1.5 for level freeways) given by Highway capacity manual of USA (TRB, 2000) as observed from Table 4. This may be attributed to the diverse static and dynamic characteristics of vehicles and complex vehicular interactions that prevail under heterogeneous traffic conditions with poor lane discipline in developing countries like India.

10.3. Capacity values

The capacity estimated from this study for Indian expressways has been compared with the capacity values given obtained from multi-country reports (Bang et al (2011)). There is a great degree of difference in the capacity values of different countries, by virtue of the differences in vehicle characteristics, traffic composition, driver behaviour and lane discipline. In Brazil, the capacity suggested for freeways is 2500 PCU/hour/lane. US-HCM (TRB, 2000) suggests a maximum flow rate on a basic freeway as 2400 PCU/hour/lane. In Indonesia(DGH, 1995) the capacity of four lane divided intercity roads is given as 1900 LVU/hour/lane where LVU refers to light vehicle units The manuals of highway capacity in most of the countries prescribe that average capacity per lane on different highways is equal. They assume that highway capacity is constantly proportioned to its number of lanes. As an example, in China, the capacity manual prescribes an average capacity per lane on uninterrupted multilane highway as 2200 PCU/h, regardless of the number of lanes (Bang et al (2011)).In this study, the capacity of the six-lane expressway facility is found to be approximately 7595 PCU/hour/direction as simulated under heterogeneous traffic conditions in VISSIM, which comes out to be 2532 PCU/hour/lane. Nevertheless, it should be noted that such a lane based capacity value is hardly relevant, when there is no lane discipline on Indian Expressways.

11. Conclusions

The study yielded out many interesting conclusions. The micro-simulation model VISSIM is suitable to simulating and hence studying heterogeneous traffic flow in expressways to a satisfactory extent. It is found that, the estimated PCU values of the different categories of vehicles of the heterogeneous traffic are accurate at 5% level of significance. For all categories of vehicles, the PCU of a given vehicle category decreases with increase in volume capacity ratio. This is due to the decreasing speed difference as volume increases from free flow to that at capacity. The PCU value of all categories of vehicles decreases when their proportion increases in the traffic stream. This is due to the platooning effect of trucks. The capacity of the six-lane expressway facility is found to be approximately 7595 PCU/hour/direction as simulated under heterogeneous traffic conditions in VISSIM. It is found that due to the complex nature of interaction between vehicles under the heterogeneous traffic condition, the PCU estimates made through simulation for different types of vehicles of heterogeneous traffic, significantly changes with change in traffic volume level.

Acknowledgements

The authors would like to thank Central Road Research Institute (CRRI), New Delhi India for providing the traffic data used in this study. They would also like to thank PTV AG, Germany for providing the software VISSIM used in this study.

References

Al-Kaisy, A.,Hall. F., & Reisman, E. (2002). Developing passenger car equivalents for heavy vehicles on freeways during queue discharge flow. *Transportation Research Part A*, Vol.36, pp.725-742.

Al-Kaisy, A., Jung, Y., & Rakha, H. (2005). Developing Passenger Car Equivalency Factors for Heavy Vehicles during Congestion. *Journal of Transportation Engineering*, Vol.131, pp. 514-523.

Arasan, V. T., & Koshy, R. Z. (2003). Headway distribution of heterogeneous traffic on urban arterials. *Journal of Institution of Engineers (India)*, Vol.84, pp. 210–215.

Arasan, V. T., & Koshy, R. Z.(2005). Methodology for modeling highly heterogeneous traffic flow. *Journal of Transportation Engineering*, Vol.131, pp. 544 – 551.

Arkatkar, S. S., & Arasan V. T. (2010). Effect of Gradient and its Length on Performance of Vehicles under Heterogeneous Traffic Conditions. *Journal of Transportation Engineering*, Vol.136, pp. 1120-1136.

Bang, K. L., Nissan, A., & Koutsopoulos, H. N. (2011), Country Reports, *the 6th International Symposium on Highway Capacity and Quality of Service*, Stockholm, Sweden.

Basu, D., Maitra, S. R., & B. Maitra (2006). Modeling passenger car equivalency at an urban mid-block using stream speed as measure of equivalence. *Journal of European Transport*, Vol.34, pp. 75-87.

Chandra, S. (2004). Capacity estimation procedure for two lane roads under mixed traffic conditions. *Journal of Indian Road Congress*, Vol.165, pp. 139-170.

Chandra, S., & Kumar, U. (2003).Effect of lane width on capacity under mixed traffic conditions in India. *Journal of Transportation Engineering*, Vol.129, pp.155-160.

Chandra, S., P. K. Sikdar. & V. Kumar (1995) Dynamic PCU estimation of capacity on urban roads. *Indian Highways*, Vol.23, pp.17– 28.

Craus, J., Polus, A., & Grinberg, I. A. (1980).Revised method for the determination of passenger car equivalencies. *Transportation Research Part A*, Vol.14, pp.241-246.

Dey, P. P., S. Chandra ., & S. Gangopadhyay. (2008). Simulation of mixed traffic flow on two-lane roads. *Journal of Transportation Engineering*, ASCE, Vol.134, pp.361-369.

Directorate General of Highways (DGH) - Ministry of Public Works. (1995), Indonesian highway capacity manual- Part-II, Interurban roads", Report No: 05/T/Bt/1995.

Fellendorf, M., & Vortisch, P. (2001).Validation of the microscopic traffic flow model VISSIM in different real-world situations. *Proceedings of 80th Annual Meeting of the Transportation Research Board*, Washington D.C.

Hossain, M.J. (2004).Calibration of the microscopic traffic flow simulation model VISSIM for urban conditions in Dhaka city.*Master thesis,* University of Karlsruhe, Germany.

Huber, M. J. (1982). Estimation of passenger car equivalents of trucks in traffic stream. *Transportation Research Record*, Vol.869, pp.60-70.

Keller, E., & Saklas, J. (1984). Passenger car equivalents from network simulation. *Journal of Transportation Engineering*, ASCE, Vol.110, pp. 397-411.

Krammes, R. A., &Crowley,K. W.(1986). Passenger car equivalents for trucks on level freeway segments. *Transportation Research Record*, Vol.1091, pp. 10-17.

Linzer, E., Roess,R., & McShane.W. (1979). Effect of trucks, buses, and recreational vehicles on freeway capacity and service volume. *Transportation Research Record*, Vol.699, pp. 17-24.

Matsuhashi, N., Hyodo, T., &Takahashi, Y. (2005). Image processing analysis on motorcycle oriented mixed traffic flow in Vietnam. *Proceedings of Eastern Asia society for transportation studies (EAST)*, Tokyo, pp. 929–944.

Ministry of Road Transport & Highways (India) (2010). Guidelines for Expressways, Part I& II, *Indian Roads Congress*, New Delhi, I73-I87.

Tiwari, G., Fazio, J., & Pavithravas, S. (2000).Passenger car units forheterogeneous traffic using a modified density method. *Proceedings of 4th International Symposium on Highway Capacity*, Maui, Hawaii, pp. 246-257.

TRB. (2000).Highway Capacity Manual,National Research Council, *Transportation Research Board*, Washington, D.C.

Van Aerde, M., & Yagar, S. (1984).Capacity, speed, and platooning vehicle equivalents for two-lane rural highways. *Transportation Research Record*, Vol. 911, pp. 58-67.

Velmurugan, S., Errampalli, M., & Reddy, T. S. (2002). "Changing operating speeds on rural highways."*Proceedings of Emerging Trends in Road Transport (RORTRAN)*, Kharagpur, India, PP. 529-540.

Velmurugan, S., Errampalli, M., Ravinder, K., & Gangopadhyay, S. (2009). Updation of road user cost for economic evaluation of road projects.*Indian Journal of Traffic Management*, pp. 205-225.

Velmurugan, S., Errampalli, M., Ravinder, K., & Sitaramanjaneyulu, K., and Gangopadhyay, S. (2010). Critical evaluation of roadway capacity of multi-lane high speed corridors under heterogeneous traffic conditions through traditional and microscopic simulation models. *Journal of Indian Roads Congress*, pp. 235-264.

Webster, N., & L. Elefteriadou. (1999). A simulation study of truck passenger car equivalents (PCE) on basic freeway sections. *Transportation Research Part B*, Vol. 33, pp. 323-336.

Werner, A., & J. Morrall. (1976). Passenger car equivalencies of trucks, buses, and recreational vehicles for two-lane rural highways. *Transportation Research Record*, Vol. 615, pp.10-17.

Zhang, G., Wang, Y., Wei, H., &Yi, P.(2008). A feedback based dynamic tolling algorithm for high-occupancy toll lane operations. *Transportation Research Record*, Vol. 2065, pp. 54-63.